# Introduction to Software Testing
## *(2nd edition)*
## Chapter 7.1, 7.2

# Overview Graph Coverage Criteria

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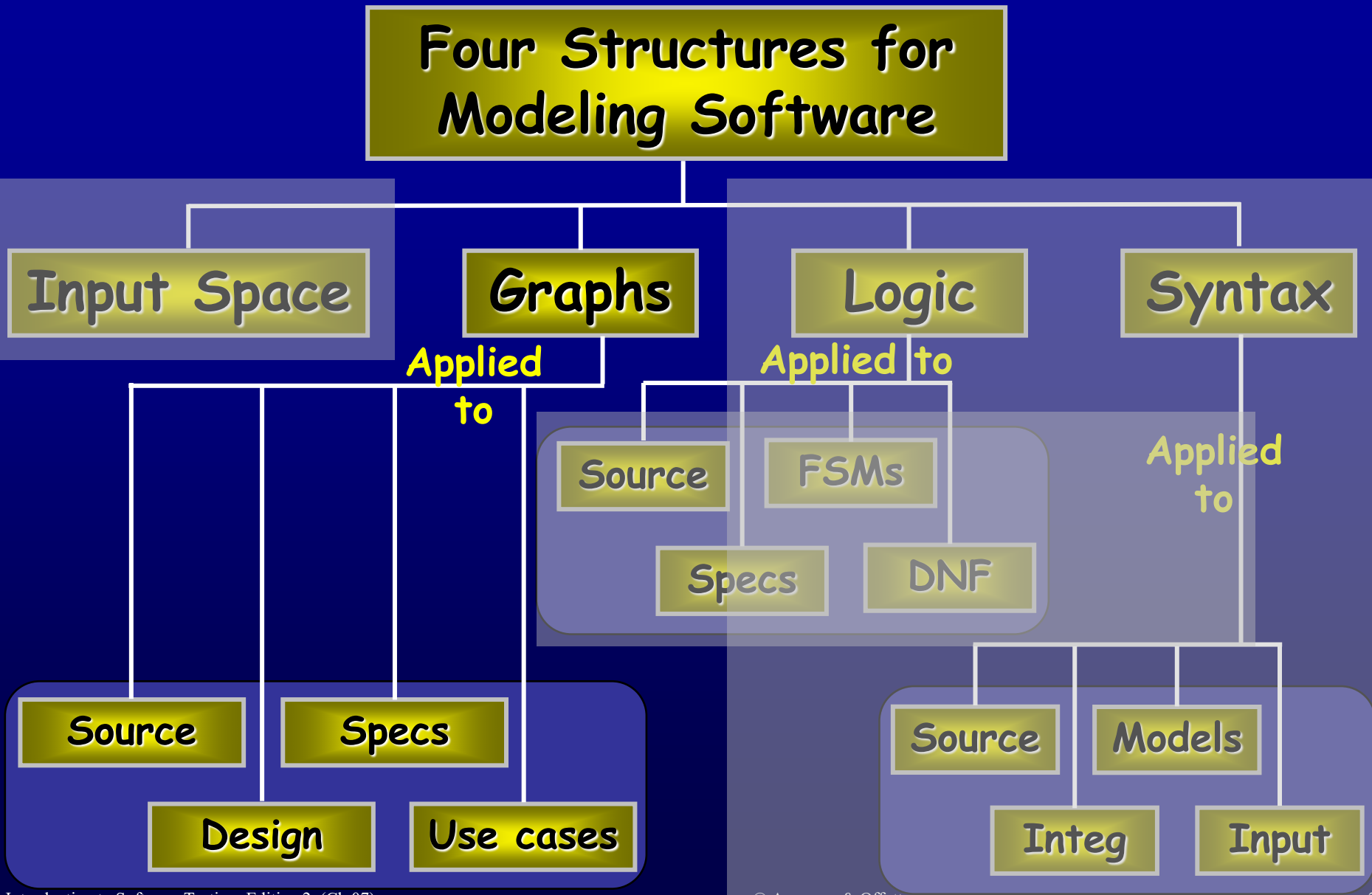
# Ch. 7 : Graph Coverage



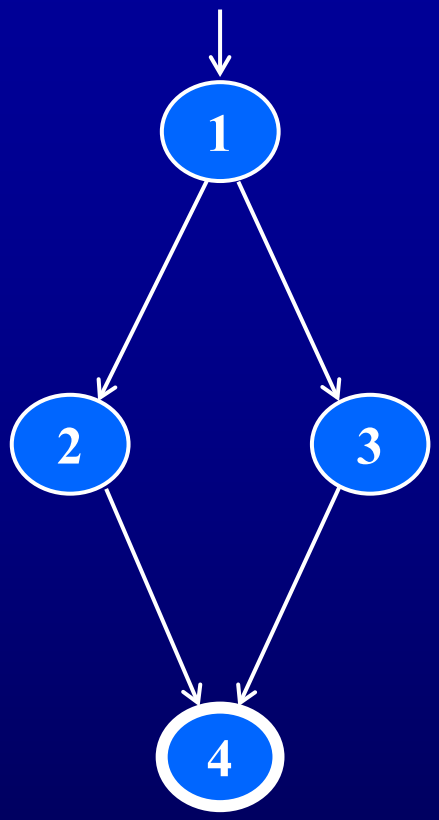
# Covering Graphs (7.1)

- Graphs are the most commonly used structure for testing
- Graphs can come from many sources
  - Control flow graphs
  - Design structure
  - FSMs and statecharts
  - Use cases
- Tests usually are intended to "cover" the graph in some way

# Definition of a Graph

- A set $N$ of nodes, $N$ is not empty
- A set $N_0$ of initial nodes, $N_0$ is not empty
- A set $N_f$ of final nodes, $N_f$ is not empty
- A set $E$ of edges, each edge from one node to another
  - ( $n_i$ , $n_j$ ), $i$ is predecessor, $j$ is successor

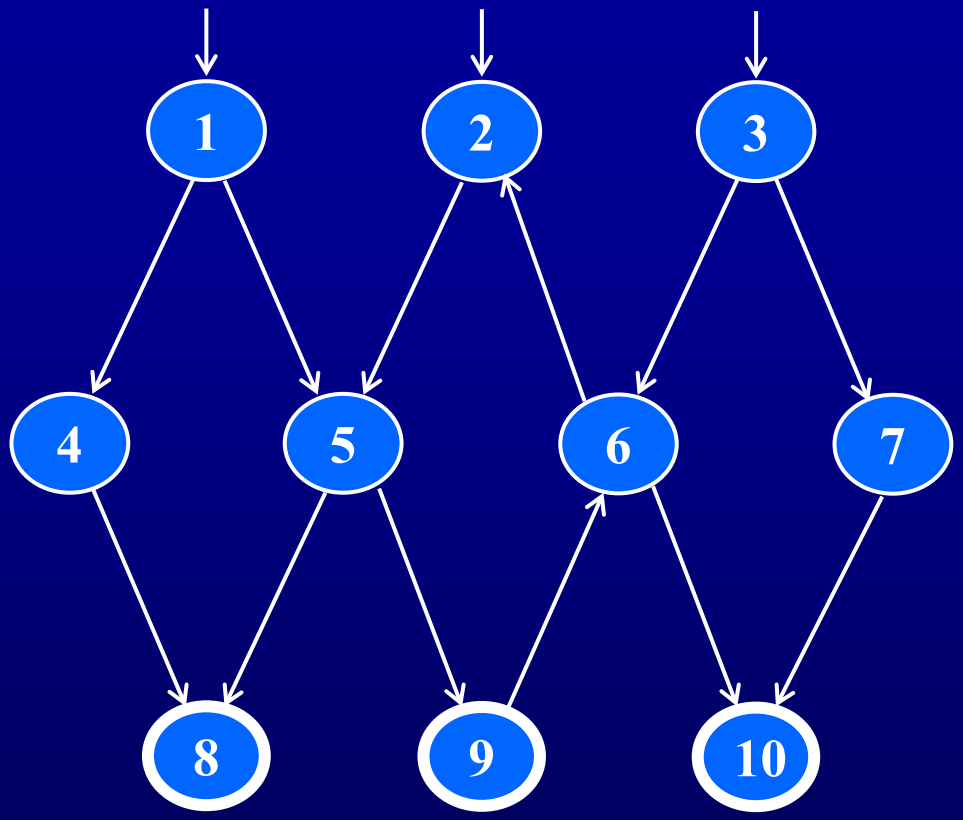
# Example Graphs




$N_0 = \{ 1 \}$

$N_f = \{ 4 \}$

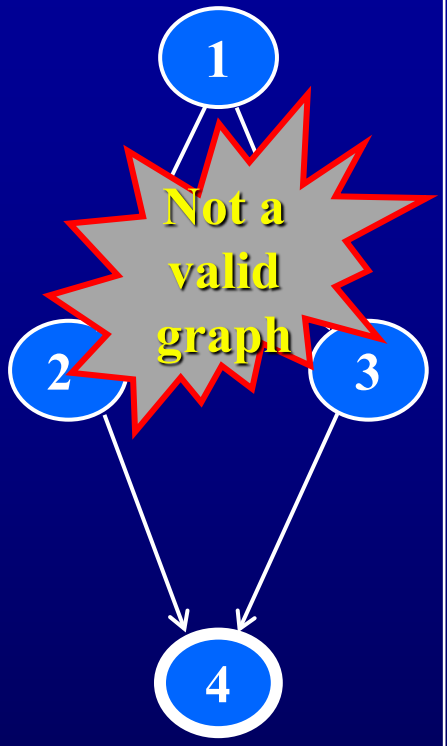
$E = \{ (1,2), (1,3), (2,4), (3,4) \}$




$N_0 = \{ 1, 2, 3 \}$

$N_f = \{ 8, 9, 10 \}$

$E = \{ (1,4), (1,5), (2,5), (3,6), (3, 7), (4, 8), (5,8), (5,9), (6,2), (6,10), (7,10) (9,6) \}$



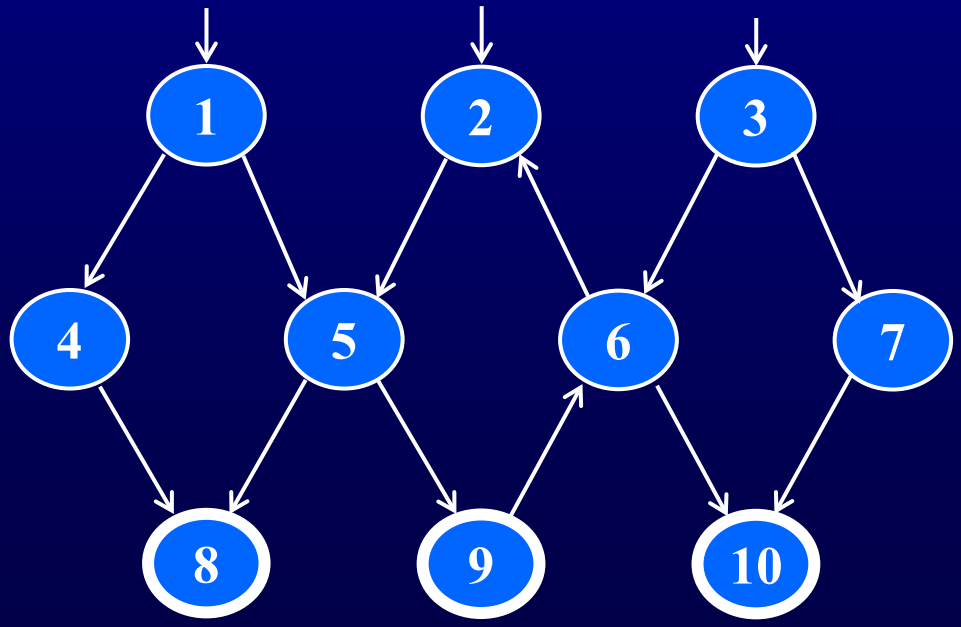

$N_0 = \{ \}$

$N_f = \{ 4 \}$

$E = \{ (1,2), (1,3), (2,4), (3,4) \}$

# Paths in Graphs

- Path : A sequence of nodes – $[n_1, n_2, \ldots, n_M]$
  - Each pair of nodes is an edge
- Length : The number of edges
  - A single node is a path of length 0
- Subpath : A subsequence of nodes in $p$ is a subpath of $p$




**A Few Paths**

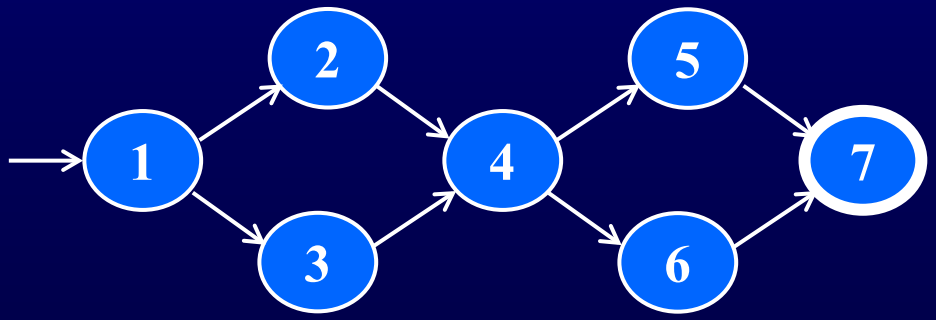
[ 1, 4, 8 ]

[ 2, 5, 9, 6, 2 ]

[ 3, 7, 10 ]

# Test Paths and SESEs

- Test Path : A path that starts at an initial node and ends at a final node
- Test paths represent execution of test cases
  - Some test paths can be executed by many tests
  - Some test paths cannot be executed by any tests
- SESE graphs : All test paths start at a single node and end at another node
  - Single-entry, single-exit
  - N0 and Nf have exactly one node




**Double-diamond graph**

**Four test paths**

**[1, 2, 4, 5, 7]**
**[1, 2, 4, 6, 7]**
**[1, 3, 4, 5, 7]**
**[1, 3, 4, 6, 7]**

# Visiting and Touring

- Visit : A test path *p* *visits* node *n* if *n* is in *p*

  A test path *p* *visits* edge e if e is in *p*
- Tour : A test path *p* *tours* subpath *q* if *q* is a subpath of *p*

**Path [ 1, 2, 4, 5, 7 ]**

**Visits nodes 1, 2, 4, 5, 7**

**Visits edges (1, 2), (2, 4), (4, 5), (5, 7)**

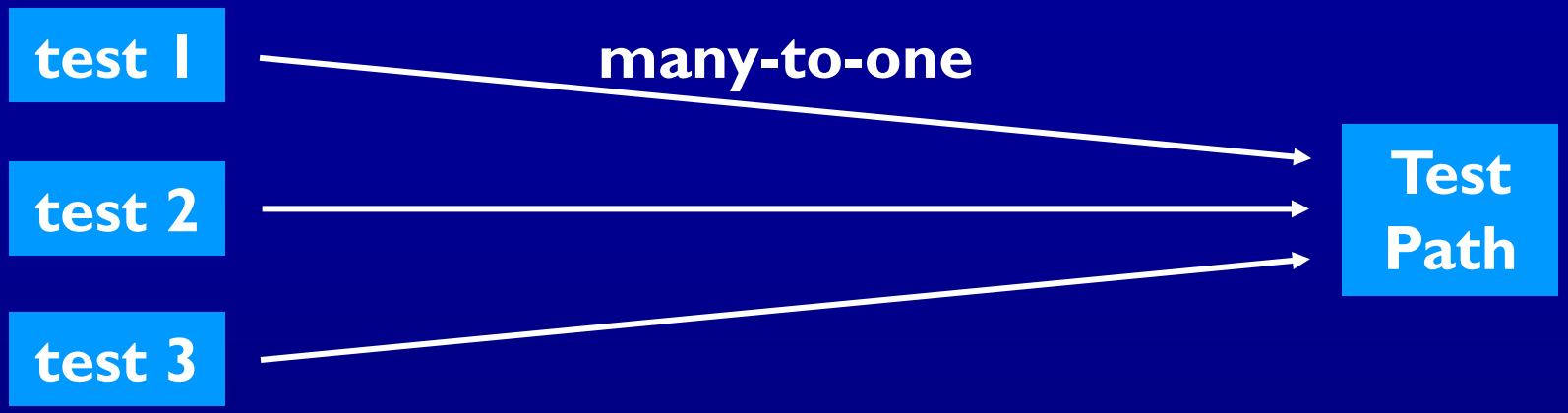
**Tours subpaths [1, 2, 4], [2, 4, 5], [4, 5, 7], [1, 2, 4, 5], [2, 4, 5, 7], [1, 2, 4, 5, 7]**

***(Also, each edge is technically a subpath)***

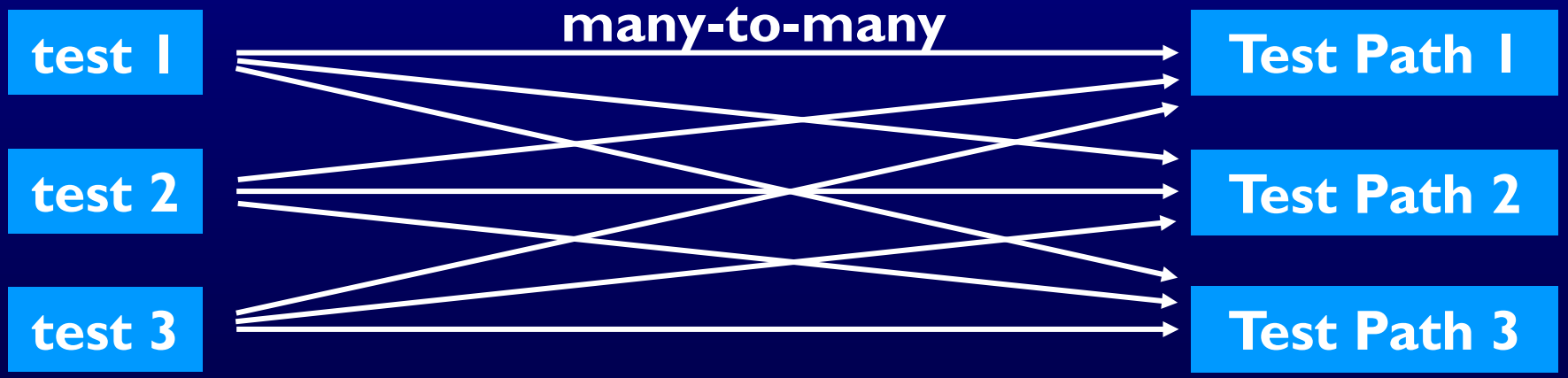
# Tests and Test Paths

- path (*t*) : The test path executed by test *t*
- path (*T*) : The set of test paths executed by the set of tests *T*
- Each test executes one and only one test path
  - Complete execution from a start node to an final node
- A location in a graph (node or edge) can be reached from another location if there is a sequence of edges from the first location to the second
  - *Syntactic reach* : A subpath exists in the graph
  - *Semantic reach* : A test exists that can execute that subpath
  - This distinction will become important in section 7.3

# Tests and Test Paths




**Deterministic software–test always executes the same test path**




**Non-deterministic software–the same test can execute different test paths**

# Testing and Covering Graphs (7.2)

- We use graphs in testing as follows :
  - Develop a model of the software as a graph
  - Require tests to visit or tour specific sets of nodes, edges or subpaths
- Test Requirements (TR) : Describe properties of test paths
- Test Criterion : Rules that define test requirements
- Satisfaction : *Given a set TR of test requirements for a criterion C, a set of tests T satisfies C on a graph if and only if for every test requirement in TR, there is a test path in path(T) that meets the test requirement tr*
- Structural Coverage Criteria : Defined on a graph just in terms of nodes and edges
- Data Flow Coverage Criteria : Requires a graph to be annotated with references to variables

# Node and Edge Coverage

- The first (and simplest) two criteria require that each node and edge in a graph be executed

**Node Coverage (NC) : Test set *T* satisfies node coverage on graph *G* iff for every syntactically reachable node *n* in *N*, there is some path *p* in *path(T)* such that *p* visits *n*.**

- This statement is a bit cumbersome, so we abbreviate it in terms of the set of test requirements

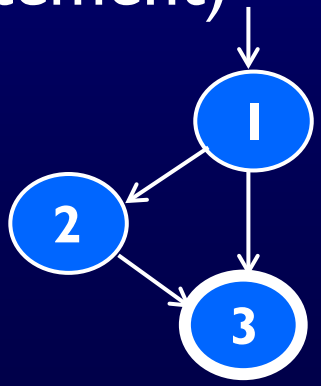
**Node Coverage (NC) : TR contains each reachable node in G.**

# Node and Edge Coverage

- Edge coverage is slightly stronger than node coverage

**Edge Coverage (EC) : TR contains each reachable path of length up to 1, inclusive, in G.**

- The phrase "*length up to 1*" allows for graphs with one node and no edges
- NC and EC are only different when there is an edge and another subpath between a pair of nodes (as in an "if-else" statement)

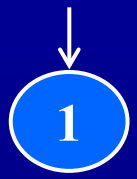



**Node Coverage : TR = { 1, 2, 3 }**
**Test Path = [ 1, 2, 3 ]**

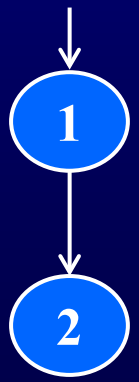
**Edge Coverage : TR = { (1, 2), (1, 3), (2, 3) }**
**Test Paths = [ 1, 2, 3 ]**
**[ 1, 3 ]**

# Paths of Length 1 and 0

- A graph with only one node will not have any edges




- It may seem trivial, but formally, Edge Coverage needs to require Node Coverage on this graph
- Otherwise, Edge Coverage will not subsume Node Coverage
  - So we define "length up to 1" instead of simply "length 1"
- We have the same issue with graphs that only have one edge – for Edge-Pair Coverage …

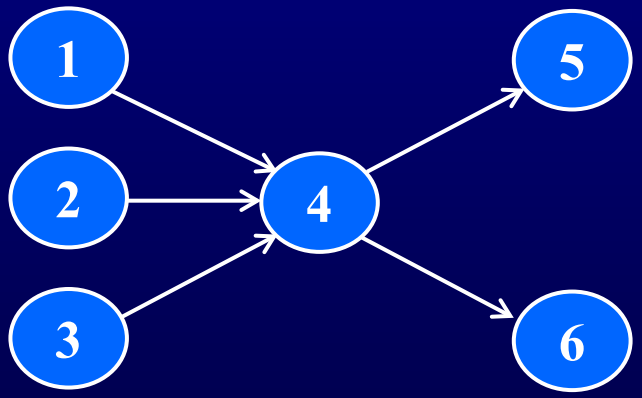


# Covering Multiple Edges

- Edge-pair coverage requires pairs of edges, or subpaths of length 2

**Edge-Pair Coverage (EPC) : TR contains each reachable path of length up to 2, inclusive, in G.**

- The phrase "length up to 2" is used to include graphs that have less than 2 edges




**Edge-Pair Coverage :**

**TR = { [1,4,5], [1,4,6], [2,4,5], [2,4,6], [3,4,5], [3,4,6] }**

- The logical extension is to require all paths …

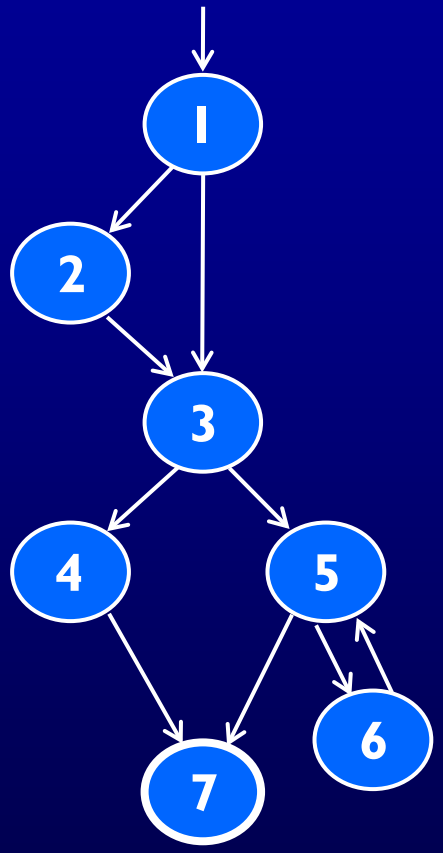
# Covering Multiple Edges

**Complete Path Coverage (CPC) : TR contains all paths in G.**

Unfortunately, this is impossible if the graph has a loop, so a weak compromise makes the tester decide which paths:

**Specified Path Coverage (SPC) : TR contains a set S of test paths, where S is supplied as a parameter.**

# Structural Coverage Example




**Node Coverage**

TR = { 1, 2, 3, 4, 5, 6, 7 }

Test Paths: [ 1, 2, 3, 4, 7 ] [ 1, 2, 3, 5, 6, 5, 7 ]

**Edge Coverage**

TR = { (1,2), (1, 3), (2, 3), (3, 4), (3, 5), (4, 7), (5, 6), (5, 7), (6, 5) }

Test Paths: [ 1, 2, 3, 4, 7 ] [1, 3, 5, 6, 5, 7 ]

**Edge-Pair Coverage**

TR = {[1,2,3], [1,3,4], [1,3,5], [2,3,4], [2,3,5], [3,4,7], [3,5,6], [3,5,7], [5,6,5], [6,5,6], [6,5,7] }

Test Paths: [ 1, 2, 3, 4, 7 ] [ 1, 2, 3, 5, 7 ] [ 1, 3, 4, 7 ] [ 1, 3, 5, 6, 5, 6, 5, 7 ]

**Complete Path Coverage**

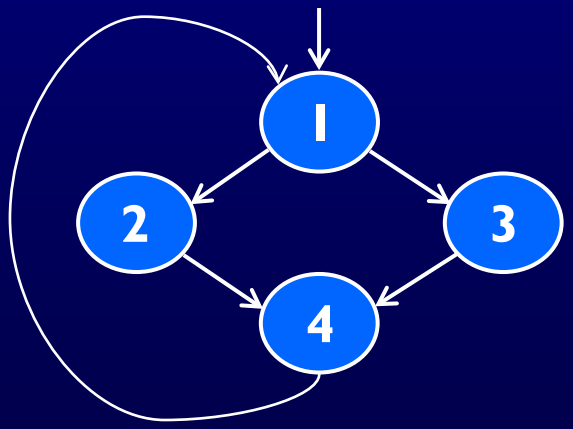
Test Paths: [ 1, 2, 3, 4, 7 ] [ 1, 2, 3, 5, 7 ] [ 1, 2, 3, 5, 6, 5, 6 ] [ 1, 2, 3, 5, 6, 5, 6, 5, 7 ] [ 1, 2, 3, 5, 6, 5, 6, 5, 6, 5, 7 ] ...

# Handling Loops in Graphs

- If a graph contains a loop, it has an infinite number of paths
- Thus, CPC is not feasible
- SPC is not satisfactory because the results are subjective and vary with the tester
- Attempts to "deal with" loops:
  - 1970s : Execute cycles once ([4, 5, 4] in previous example, informal)
  - 1980s : Execute each loop, exactly once (formalized)
  - 1990s : Execute loops 0 times, once, more than once (informal description)
  - 2000s : Prime paths (touring, sidetrips, and detours)

# Simple Paths and Prime Paths

- Simple Path : *A path from node ni to nj is simple if no node appears more than once, except possibly the first and last nodes are the same*
  - No internal loops
  - A loop is a simple path
- Prime Path : *A simple path that does not appear as a proper subpath of any other simple path*




**Simple Paths** : [1,2,4,1], [1,3,4,1], [2,4,1,2], [2,4,1,3], [3,4,1,2], [3,4,1,3], [4,1,2,4], [4,1,3,4], [1,2,4], [1,3,4], [2,4,1], [3,4,1], [4,1,2], [4,1,3], [1,2], [1,3], [2,4], [3,4], [4,1], [1], [2], [3], [4]

**Prime Paths** : [2,4,1,2], [2,4,1,3], [1,3,4,1], [1,2,4,1], [3,4,1,2], [4,1,3,4], [4,1,2,4], [3,4,1,3]

# Prime Path Coverage

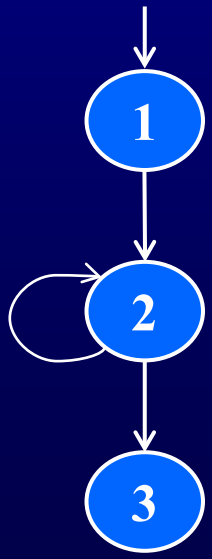
- A simple, elegant and finite criterion that requires loops to be executed as well as skipped

**Prime Path Coverage (PPC) : TR contains each prime path in G.**

- Will tour all paths of length 0, 1, …
- That is, it subsumes node and edge coverage
- PPC almost, but not quite, subsumes EPC …

# PPC Does Not Subsume EPC

- If a node *n* has an edge to itself (*self edge*), EPC requires [*n, n, m*] and [*m, n, n*]
- [*n, n, m*] is not prime
- Neither [*n, n, m*] nor [*m, n, n*] are simple paths (not prime)




**EPC Requirements :**

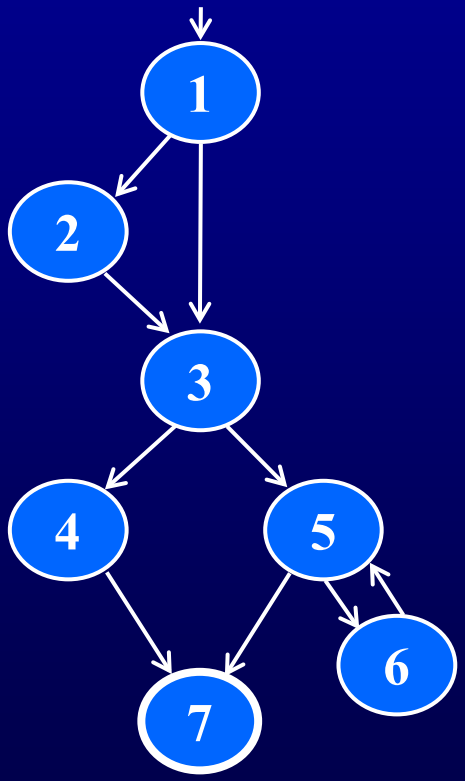
**TR = { [1,2,3], [1,2,2], [2,2,3], [2,2,2] }**

**PPC Requirements :**

**TR = { [1,2,3], [2,2] }**

# Prime Path Example

- The previous example has 38 simple paths
- Only nine *prime paths*




**Prime Paths**

[1, 2, 3, 4, 7]
[1, 2, 3, 5, 7]
[1, 2, 3, 5, 6]
[1, 3, 4, 7]
[1, 3, 5, 7]
[1, 3, 5, 6]
[6, 5, 7]
[6, 5, 6]
[5, 6, 5]

**Execute loop 0 times**

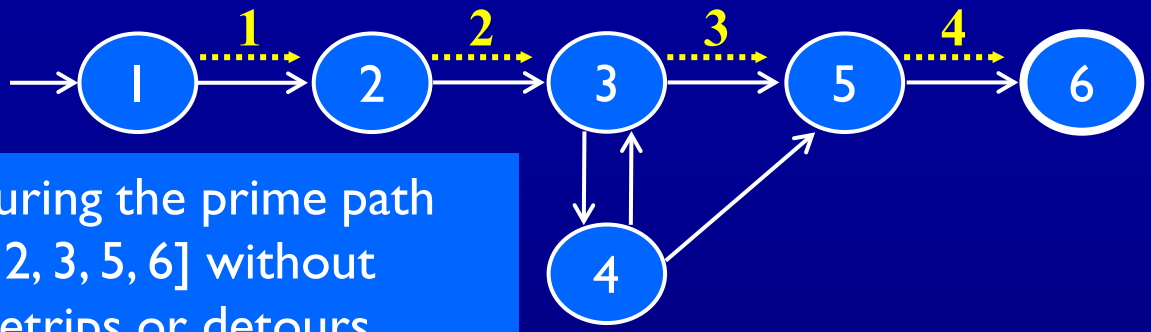
**Execute loop once**

**Execute loop more than once**

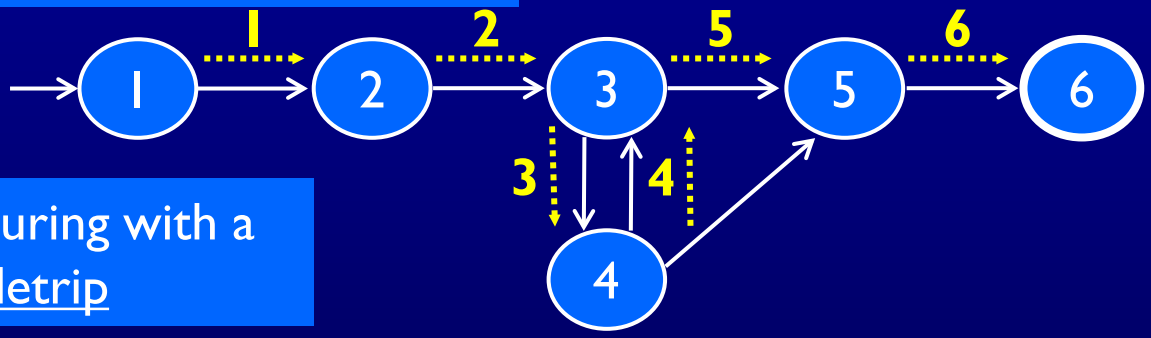
# Touring, Sidetrips, and Detours

- Prime paths do not have internal loops … test paths might
- Tour : *A test path p tours subpath q if q is a subpath of p*
- Tour With Sidetrips : *A test path p tours subpath q with sidetrips iff every edge in q is also in p in the same order*
  - The tour can include a sidetrip, as long as it comes back to the same node
- Tour With Detours : *A test path p tours subpath q with detours iff every node in q is also in p in the same order*
  - The tour can include a detour from node *ni*, as long as it comes back to the prime path at a successor of *ni*

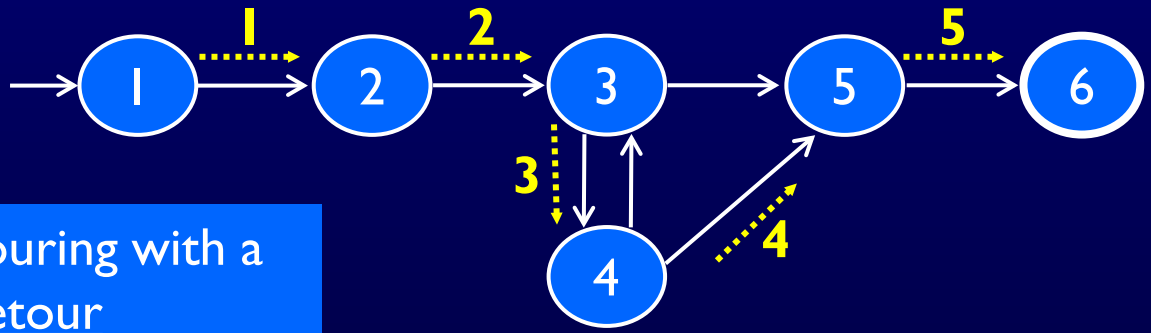
# Sidetrips and Detours Example




Touring the prime path [1, 2, 3, 5, 6] without sidetrips or detours




Touring with a sidetrip




Touring with a detour

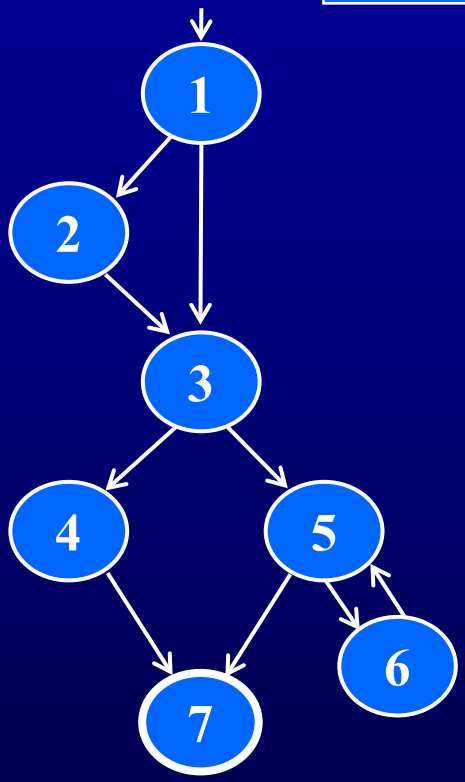
# Infeasible Test Requirements

- An infeasible test requirement cannot be satisfied
  - Unreachable statement (dead code)
  - Subpath that can only be executed with a contradiction ($X > 0$ and $X < 0$)
- Most test criteria have some infeasible test requirements
- It is usually undecidable whether all test requirements are feasible
- When sidetrips are not allowed, many structural criteria have more infeasible test requirements
- However, always allowing sidetrips weakens the test criteria

**Practical recommendation—Best Effort Touring**

- **Satisfy as many test requirements as possible without sidetrips**
- **Allow sidetrips to try to satisfy remaining test requirements**

# Simple & Prime Path Example




**Simple paths**

**Len 0**
[1]
[2]
[3]
[4]
[5]
[6]
[7] !

**Len 1**
[1, 2]
[1, 3]
[2, 3]
[3, 4]
[3, 5]
[4, 7] !
[5, 7] !
[5, 6]
[6, 5]

**Len 2**
[1, 2, 3]
[1, 3, 4]
[1, 3, 5]
[2, 3, 4]
[2, 3, 5]
[3, 4, 7] !
[3, 5, 7] !
[3, 5, 6] !
[5, 6, 5] *
[6, 5, 7] !
[6, 5, 6] *

**Len 3**
[1, 2, 3, 4]
[1, 2, 3, 5]
[1, 3, 4, 7] !
[1, 3, 5, 7] !
[1, 3, 5, 6] !
[2, 3, 4, 7] !
[2, 3, 5, 6] !
[2, 3, 5, 7] !

**Len 4**
[1, 2, 3, 4, 7] !
[1, 2, 3, 5, 7] !
[1, 2, 3, 5, 6] !

***Prime Paths***

# Round Trips

- Round-Trip Path : *A prime path that starts and ends at the same node*

**Simple Round Trip Coverage (SRTC) : TR contains at least one round-trip path for each reachable node in G that begins and ends a round-trip path.**

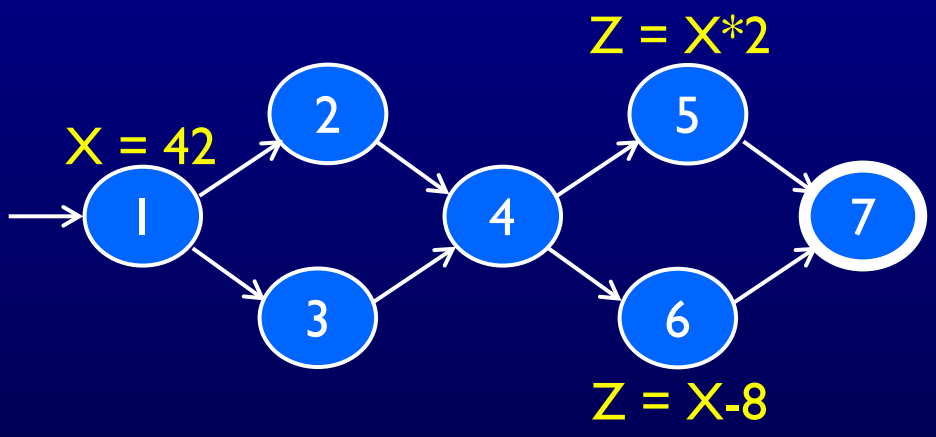
**Complete Round Trip Coverage (CRTC) : TR contains all round-trip paths for each reachable node in G.**

- These criteria omit nodes and edges that are not in round trips
- Thus, they do not subsume edge-pair, edge, or node coverage

# Data Flow Criteria

**Goal: Try to ensure that values are computed and used correctly**

- Definition (def) : A location where a value for a variable is stored into memory
- Use : A location where a variable's value is accessed




Defs: def (1) = {X}

def (5) = {Z}

def (6) = {Z}

Uses: use (5) = {X}

use (6) = {X}

The values given in defs should reach at least one, some, or all possible uses

# DU Pairs and DU Paths

- def (n) or def (e) : The set of variables that are defined by node n or edge e
- use (n) or use (e) : The set of variables that are used by node n or edge e

- DU pair : A pair of locations ($l_i$, $l_j$) such that a variable *v* is defined at $l_i$ and used at $l_j$

- Def-clear : A path from $l_i$ to $l_j$ is *def-clear* with respect to variable *v* if *v* is not given another value on any of the nodes or edges in the path
- Reach : If there is a def-clear path from $l_i$ to $l_j$ with respect to *v*, the def of *v* at $l_i$ reaches the use at $l_j$

- du-path : A simple subpath that is def-clear with respect to *v* from a def of *v* to a use of *v*
- du ($n_i$, $n_j$, *v*) – the set of du-paths from $n_i$ to $n_j$
- du ($n_i$, *v*) – the set of du-paths that start at $n_i$

# Touring DU-Paths

- A test path *p* *du-tours* subpath *d* with respect to *v* if *p* tours *d* and the subpath taken is def-clear with respect to *v*
- Sidetrips can be used, just as with previous touring
- Three criteria
  - Use every def
  - Get to every use
  - Follow all du-paths

# Data Flow Test Criteria

- First, we make sure every def reaches a use

**All-defs coverage (ADC) : For each set of du-paths $S$ = $du$ ($n$, $v$), TR contains at least one path $d$ in $S$.**

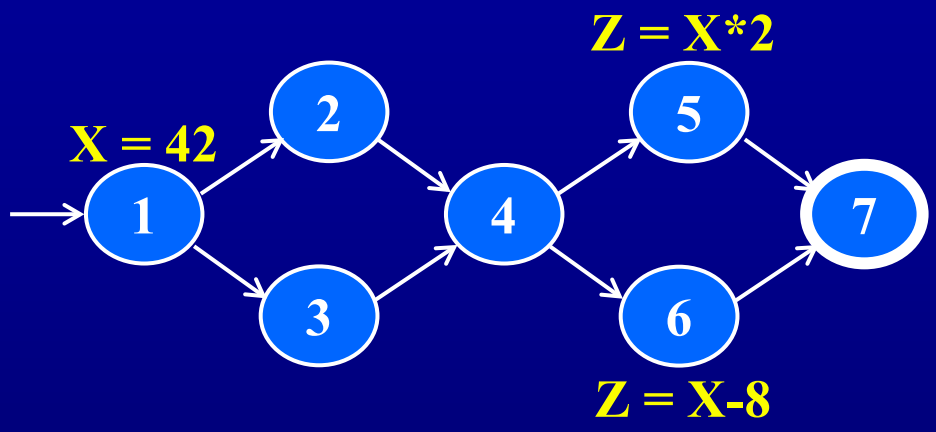
- Then we make sure that every def reaches all possible uses

**All-uses coverage (AUC) : For each set of du-paths to uses $S$ = $du$ ($n_i$, $n_j$, $v$), TR contains at least one path $d$ in $S$.**

- Finally, we cover all the paths between defs and uses

**All-du-paths coverage (ADUPC) : For each set $S$ = $du$ ($ni$, $nj$, $v$), TR contains every path $d$ in $S$.**

# Data Flow Testing Example

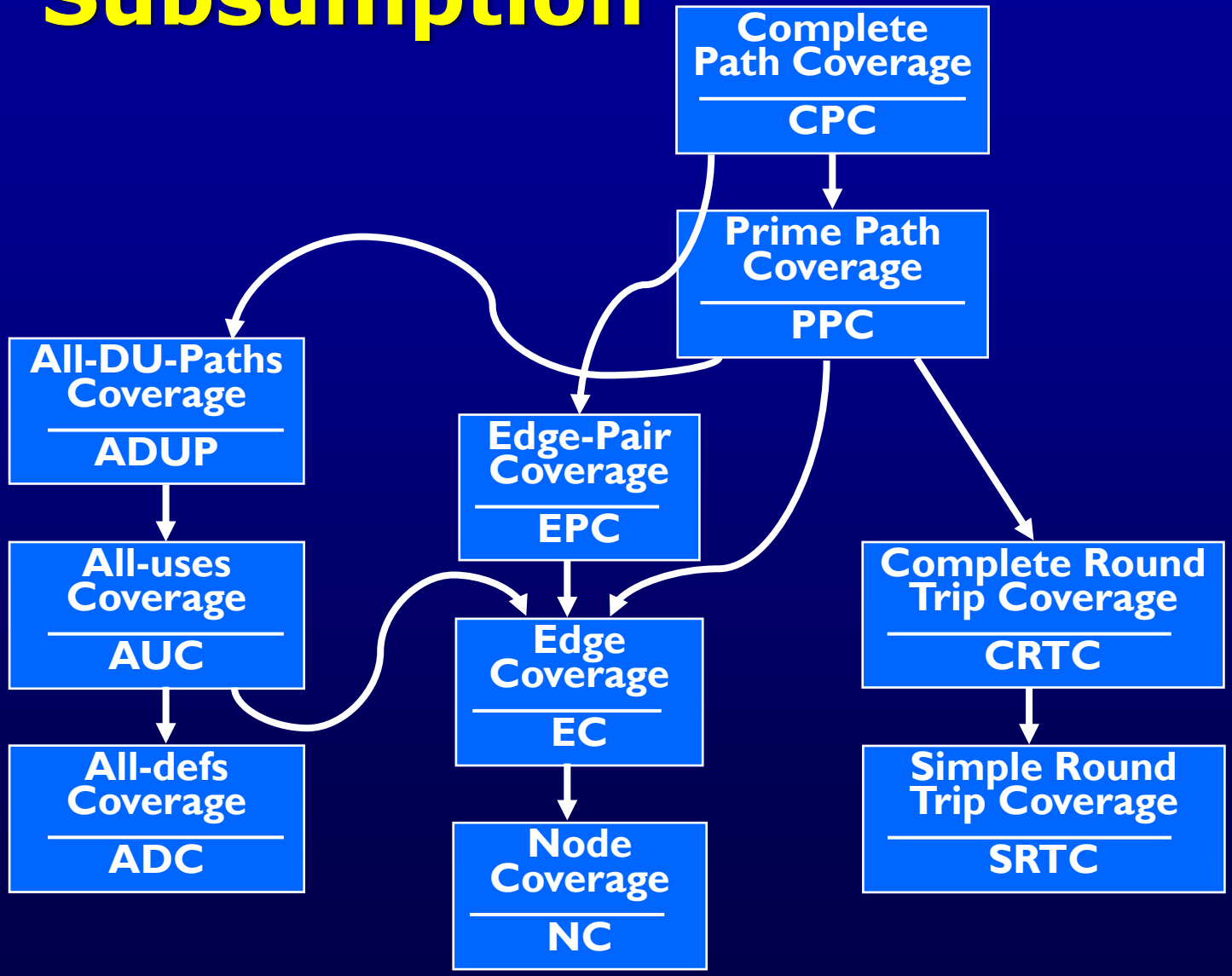



| All-defs for *X* |
| --- |
| [ 1, 2, 4, 5 ] |

| All-uses for *X* |
| --- |
| [ 1, 2, 4, 5 ] |
| [ 1, 2, 4, 6 ] |

| All-du-paths for *X* |
| --- |
| [ 1, 2, 4, 5 ] |
| [ 1, 3, 4, 5 ] |
| [ 1, 2, 4, 6 ] |
| [ 1, 3, 4, 6 ] |

# Graph Coverage Criteria Subsumption



# Summary 7.1-7.2

- Graphs are a very powerful abstraction for designing tests
- The various criteria allow lots of cost / benefit tradeoffs
- These two sections are entirely at the "design abstraction level" from chapter 2
- Graphs appear in many situations in software
  - As discussed in the rest of chapter 7